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Introduction to Geothermal Energy

Geothermal energy systems are one option for providing energy services. They take advantage of the ground and the energy it contains. Sometimes ground energy is the basic ground at its natural temperature, which is mainly affected by ambient conditions. At other times, the ground is at an elevated temperature. Considering the current level of geothermal energy use and future energy needs, geothermal energy sources show great potential for contributing a larger fraction of the world's energy needs.

Archaeological evidence shows that geothermal energy was first used by ancient peoples, including the Romans, Chinese, and Native Americans. They used hot mineral springs as a source of heat for bathing, cooking, and heating. The minerals in water from these springs also served as a source of healing. While such uses of hot springs have changed over time, they are still used as a source of heat for bathing in several spas around the world. With technological developments, the use of geothermal energy has expanded to deeper levels of the earth's crust, which can be used for a wider range of applications such as domestic heating and cooling, industrial processes, and electricity generation. However, only a small fraction of available geothermal energy is currently used commercially to generate electricity or provide useful heating, in part due to the current state of the technology.

Geothermal energy systems that exploit hot reservoirs in the ground (e.g., thermal springs, geysers, ground heated by hot magma) are used mainly to generate electricity and to provide heating. Such systems are common in countries such as Iceland, Turkey and others. The global operating capacity for geothermal electricity generation from such geothermal resources is about 12.8 GW as of January 2015, spread across 24 countries, and it is expected to reach between 14.5 GW and 17.6 GW by 2020 (Geothermal Energy Association 2015).

There is another type of geothermal energy system, which provides heating and cooling using the ground. That is the type of geothermal energy that is the focus of this book. Such geothermal energy systems take advantage of the energy contained in the ground in its natural state, even when it is not at elevated temperatures due to heat within the earth. This ground energy is related to the background ground temperature and includes the ground itself and groundwater.

Geothermal Energy: Sustainable Heating and Cooling Using the Ground, First Edition.
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1.1 Features of Geothermal Energy

Ground-based energy can be used in all seasons:

- Ground-based energy can provide heating directly in winter, since the ground below the surface is often warmer than the air above. Such applications include space heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial heating uses, bathing and swimming, and snow melting. Sometimes the ground temperature is only adequate to provide preheating. The ground temperature can also be boosted via devices like heat pumps, allowing ground-based energy to provide heating at higher temperatures. The use of geothermal energy via ground-source heat pumps has grown considerably compared to the other applications, primarily due to the technology's ability to achieve high efficiency and to utilize groundwater and/or ground temperature anywhere in the world.
- Conversely, ground-based energy can provide direct cooling in summer, since the ground below the surface is often cooler than the hot air above. Again, the ground temperature may only be adequate to provide precooling. But the ground temperature can also be lowered using heat pumps operating in a cooling mode, allowing ground-based energy to provide cooling at lower temperatures.

Although the earth's ultimate geothermal energy potential cannot be estimated based on our current level of knowledge and the unpredictability of technology development, geothermal energy systems of both types are usually classified as renewable energy forms. When such geothermal energy is utilized, the temperature of the ground is returned to its elevated temperature by heat contained within hot regions in the earth, or by the effect of the ambient conditions. Discussions of the renewability of various heat sources vary for the different technologies utilizing the energy source. For example, technologies that utilize the ground at temperatures affected by the ambient conditions can be considered renewable provided the ambient conditions are sustained. The constant heat supply from solar radiation and the sustainability of the hydrological cycle (infiltration and precipitation) guarantees a constant flow of heat to the ground and the renewability of such geothermal sources. The energy replacement often occurs on a time scale comparable with that of the extraction time scale.

Sustainable geothermal energy utilization often refers to how this energy resource is used to meet current energy needs without compromising its future utilization. Estimating the long-term response of geothermal energy sources to current utilization and production capacity levels is important if we are to understand their potential contributions to sustainable development. As a renewable energy source, geothermal energy is often viewed as a contributor to sustainable development and the broader goal of sustainability, provided that they are well designed. Being sustainable goes beyond geothermal energy being a renewable energy form, and includes many of its other characteristics:

- **Availability.** Geothermal energy in the form of ground at elevated temperature is available in many parts of the world, especially in regions with seismic and volcanic activity. Geothermal energy in the form of ground at ambient temperature is available almost everywhere, although its temperature depends on the location and climate. Geothermal energy is available day and night, every day of the year, and can thus cover base-load energy needs and serve as a supplement to intermittent energy sources. The availability characteristics of intermittent renewable energy forms such as solar and wind are much different.

- **Compatibility.** Systems exploiting geothermal energy are often compatible with both centralized and distributed energy generation.
- **Affordability.** Geothermal energy is often exploitable for heating and cooling, and for electricity generation, in an affordable manner. Of course, some geothermal systems are not economically viable, but work is ongoing on several of these to improve commercial prospects.
- **Acceptability.** Most people are supportive of geothermal energy, in part because it is renewable and often economically viable, and also because geothermal energy systems are not intrusive and usually are invisible. This is not the case for many other renewable energy forms, such as solar and wind.

Barriers to deployment include high capital costs, resource development risks, lack of awareness about geothermal energy, and perceived or real environmental issues.

1.2 Geothermal Energy Systems

Geothermal energy systems can exploit hot reservoirs in the ground, often in the form of natural hot water or steam, to provide heating and electricity generation. The geothermal energy technologies that are used in electricity generation are flash technologies, including double and triple flash units, dry steam, and binary cycles. Electricity generation using flash technologies contribute to nearly 60% of the global market use, with dry steam and binary cycles accounting for 26 and 15% of the global market, respectively (Geothermal Energy Association 2015). Growth in use of such geothermal energy systems for heating and electricity generation is limited by their high capital costs. Geothermal development costs depend on resource temperature and pressure, reservoir depth and permeability, fluid chemistry, location, drilling requirements, size of development, number and type of plants (dry steam, flash, binary or hybrid) used, and whether the project is greenfield or expansion (10–15% less). Development costs are strongly affected by prices of commodities (e.g., oil, steel, and cement). Declines in oil and gas prices can decrease geothermal capital costs.

Geothermal energy systems that provide heating and cooling using the ambient ground are made up of various systems and components. Some of the main systems include ground-source heat pumps, thermal energy storage systems, and district energy (i.e., district heating and/or district cooling) capabilities. They also include many other components, such as compressors, heat exchangers, pumps and pipes. Ground-source heat pump systems are capable of providing heating and cooling in one unit. The capacity of a ground-source heat pump is selected based on the heating and cooling loads, the temperature of the ground, and other parameters. Since most areas do not have balanced heating and cooling loads, the capacity of the heat pump is often selected based on one load. In most regions in the USA, the heat pump capacity matches the cooling load and is oversized for the heating loads. In Europe, ground-source heat pumps are used in the residential sector to cover base heating loads and are integrated with another heating system that covers peak heating loads. The capacity of individual ground-source heat pump units ranges from about 1.5 t for small residential applications to over 40 t for commercial and institutional applications. Technology improvements in ground-source heat pumps are expected to improve the performance and lower the cost of heat pump technologies. Key components such as compressors and heat exchangers will likely provide the largest areas for improvement. The main goals for ground-source heat pumps are reducing capital costs and improving operating efficiency, while expanding the range of products for most of the heating and cooling applications and sub-markets in the building sector.

Thus, geothermal energy systems can provide heating and cooling using the ambient ground, and can exploit hot reservoirs in the ground to provide heating and electricity generation. Both types of geothermal energy are used in practise, and are finding increased application. But the use of geothermal energy systems that use the ground to provide heating and cooling services (the focus of this book) is growing at a particularly noteworthy rate. According to a recent report (Lund and Boyd 2015), the direct use of geothermal energy has experienced an annual growth of 7.7% in capacity over the 5-year period after 2010, with the highest installed thermal capacity in the USA, China, and Sweden. This growth is mainly attributable to the growing popularity of ground-source heat pumps. About 90 000 TJ/year of ground-source heat pump utilization was observed in 2010, and this grew to approximately 325 000 TJ/year by the end of 2014.

Although geothermal energy technologies have been around for over 40 years and are applied in many areas, they are continually undergoing research and development. These efforts allow for system improvements, advances in components and enhanced understanding. Such activity is likely to carry on in the future.

1.3 Outline of the Book

In this book, geothermal energy systems are described that utilize ground energy in conjunction with heat pumps to provide heating and cooling, in a sustainable fashion. Various topics are covered, from thermodynamic fundamentals to advanced discussions on renewability and sustainability. Many applications of such systems are also described, while theory and analysis are emphasized throughout. Detailed descriptions are provided of models for vertical geothermal heat exchangers, and a strong focus is placed on closed-loop geothermal energy systems.

In this chapter, an introduction to geothermal energy as a source of energy and technologies that can harvest it is provided. Some key features of geothermal energy systems, such as its renewability and sustainability, as well as some of its advantages are briefly described. The main components of such systems are reviewed. The aim of this chapter is to provide the reader with basic information to help develop an understanding of the overall scope and range of material that is included in this book.

In Chapter 2, fundamentals of thermodynamics, heat transfer and fluid mechanics that are related to geothermal energy systems are provided to familiarize readers with these topics and prepare them for subsequent chapters. A good knowledge of thermodynamics is important to understanding geothermal energy, especially heat pumps. Facets of thermodynamics most relevant to geothermal energy systems and their applications are introduced and particular attention is paid to the quantity exergy and the methodology derived from it, exergy analysis. Aspects of heat transfer relevant to geothermal energy systems are introduced to provide the reader with a good grounding in heat transfer, which is central to geothermal energy utilization and its application.

The three main modes of heat transfer are considered: conduction, convection, and radiation. A good grounding of fluid mechanics helps in understanding geothermal energy systems, as fluid flow problems often arise, so elements of fluid mechanics relevant to geothermal energy systems are also introduced. Finally, basic concepts about the ground are presented, since such material is fundamental to understanding ground-based geothermal systems, including information on ground temperature range and gradients, ground properties, and the existence of ground-based ecosystems and their sensitivity to human activity in the ground.

Chapter 3 provides background information on components of geothermal energy systems such as heat pumps, heat exchangers, heating, ventilating and air conditioning (HVAC) equipment and energy storage units. An understanding of these technologies is needed to analyze them and the larger energy systems that they comprise. The devices examined include heat pumps, which are cyclic devices that transfer heat from a low-temperature medium to a high-temperature medium; heat exchangers, which are devices for heat exchange processes between two media; HVAC equipment, which provides heating, cooling, humidification and dehumidification for spaces, and energy storage systems that permit harvested or otherwise available energy to be stored until such a time when it is needed or desired.

Chapter 4 focuses on thermal energy storage (TES) concepts, theory and applications. Details on thermal storage types, operation and applications are provided, for both heat and cold storage. The main thermal storage types, sensible, latent and thermochemical, are covered. A focus is placed on underground thermal energy storages, which normally are sensible storages, as they can store both hot and cold energy in the ground and thus are often integral to geothermal energy systems. Common types of underground thermal energy storage are described: soil and earth bed, borehole, aquifer, rock cavern, container/tank, and solar pond. Finally, the integration of thermal energy storage with heat pumps is examined, as such systems can be particularly beneficial for heating and cooling applications.

Geothermal heating and cooling is the focus of Chapter 5. Ground-based energy can provide heating in winter and cooling in summer, in partial or full manners. Ground-source heat pumps normally form the basis of such systems and therefore are extensively discussed. Emphasis is placed on geothermal heat exchangers (also called ground, underground and ground-coupled heat exchangers), since they facilitate the exchange of heat between a fluid and the ground. For completeness, high-temperature geothermal systems are also described, including systems that essentially use the ground as a heat source for electricity generation and heating.

General information on design considerations for geothermal energy systems and procedures for the installation of ground-source heat pump systems are provided in Chapter 6. The material on how systems are designed describes the relation to building loads and weather. Procedures in designing systems with unbalanced loads are also discussed. Building energy calculations, which are important first steps in designing any space heating and cooling system, are covered, as are building and heat pump performance considerations, heating and cooling calculations, and ground heat injection and extraction. Finally, the economics of geothermal systems, which vary according to type and application, is described.

The modeling of ground heat exchangers is examined in Chapter 7. Various models have been reported for heat transfer in borehole heat exchangers and their coupling with HVAC and building energy systems. Both analytical and numerical approaches are considered, and parameters such as moisture migration and groundwater flow, relevant boundary conditions, and solution errors are described. Groundwater and how it and its movement affects the performance of ground-source heat pump systems is assessed. Two- and three-dimensional models are covered, as are horizontal and vertical heat exchangers. Finally, the coverage is expanded to the modeling of multiple boreholes in the form of a borefield and systems with time varying heat transfer rates.

In Chapter 8, the analytical and numerical models presented in Chapter 7 are applied to various examples, involving various levels of difficulty and detail. Since the modeling approach is often selected based on the objective of modeling ground heat exchangers, the objectives of modeling the systems are described for each example, and challenges of each model example are explained. The examples include the semi-analytical modeling of two boreholes, the numerical modeling of two boreholes, the numerical modeling of a borefield, and the numerical modeling a horizontal ground heat exchanger.

The thermodynamic analysis of geothermal energy systems of various kinds is the focus of Chapter 9. Special attention is placed on the application of exergy concepts in analysis of energy systems to evaluate and optimize their design and performance. The energy systems discussed include an underground thermal storage in the form of an aquifer TES, a hybrid ground-source heat pump system, and ground-source heat pumps and underground thermal storage. A thermodynamic analysis of a complex system integrating ground-source heat pumps and underground thermal storage is featured.

Environmental factors of relevance to geothermal energy systems are covered in Chapter 10. These include reductions in greenhouse gas emissions achievable with such systems. From an environmental perspective, preserving natural habitats in the ground by avoiding drastic changes in temperature and moisture content is an important subject especially when discussing the installation of ground heat exchangers (GHEs) at various depths in the ground. Geothermal system installation can incur environmental benefits and impacts, so both are discussed. The "thermal pollution" released from ground-source heat pump systems to the ground and potentially sensitive ecosystems is described. The chapter includes material that can guide regulatory agencies and industry towards designs and installations that improve and even maximize their sustainability and reduce or minimize possible environmental impacts.

Chapter 11 covers the renewability and sustainability of geothermal energy systems. As a renewable energy source, geothermal energy is often seen to have a significant role to play as a contributor to sustainable development and, more broadly, sustainability. Particular attention is paid to the thermal interactions between ground-source heat pumps and their underground heat exchangers.

In Chapter 12, a range of case studies is presented to illustrate the application of geothermal energy systems that utilize the ground for heating and cooling as well as their advantages and disadvantages. The cases consider applications from the residential, commercial and institutional building sectors, as well as relevant utility sector entities involved in electricity generation and district heating and cooling. The case studies illustrate the context in which a geothermal energy system can be employed and assessed, and are based mainly on actual applications and drawn from various sources. The types of geothermal energy systems covered through the case studies include an underground thermal energy storage, a ground and water tank thermal energy storage for heating, a space conditioning with a heat pump and seasonal thermal storage, and an integrated system with a ground-source heat pump, thermal storage and district energy.

For further reading, many references on various aspects of geothermal systems are given, and links to websites with basic freeware for ground-source heat transfer modeling and building heating loads are provided.

References

Geothermal Energy Association (2015) Annual U.S. & Global Geothermal Power Production Report', http://geo-energy.org/reports.aspx (accessed March 9, 2016).

Lund, J.W. and Boyd, T.L. (2015) Direct utilization of geothermal energy 2015 worldwide review. *Proceedings of the World Geothermal Congress*, April 19–25, 2015, Melbourne, Australia. International Geothermal Association.